Microlensing by the Galactic Bar

HongSheng Zhao,

Dept. of Astronomy, Columbia University, NY, NY 10027 USA

David N. Spergel,

Princeton University Observatory, Princeton, NJ 08544 USA

and

R. Michael Rich

Dept. of Astronomy, Columbia University, NY, NY 10027 USA

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ABSTRACT

We compute the predicted optical depth and duration distribution of microlensing events towards Baade's window in a model composed of a Galactic disk and a bar. The bar model is a self-consistent dynamical model built out of individual orbits that has been populated to be consistent with the *COBE* maps of the Galaxy and kinematic observations of the Bulge. We find that most of the lenses are in the Bulge with a line-of-sight distance 6.25 kpc (adopting $R_0 = 8$ kpc). The microlensing optical depth of a $2 \times 10^{10} M_\odot$ bar plus a truncated disk is $(2.2 \pm 0.3) \times 10^{-6}$, consistent with the very large optical depth $(3.2 \pm 1.2) \times 10^{-6}$ found by Udalski et al. (1994). This model optical depth is enhanced over the predictions of axisymmetric models by Kiraga & Paczyński (1994, hereafter KP) by slightly more than a factor of two since the bar is elongated along the line-of-sight. The large Einstein radius and small transverse velocity dispersion also predict a longer event duration in the self-consistent bar model than the KP model. The event rate and duration distribution also depend on the lower mass cutoff of the lens mass function. With a $0.1 M_\odot$ cutoff, 5-7 events (depending on the contribution of disk lenses) with a logarithmic mean duration of 20 days are expected for the OGLE experiment according to our model, while Udalski et al. (1994) observed 9 events with durations from 8 to 62 days. On the other hand, if most of the lenses are brown dwarfs, our model predicts too many short duration events. A KS test finds only 7% probability for the model with $0.01 M_\odot$ cutoff to be consistent with current data.

Subject headings: dark matter - galactic structure - dynamics - gravitational lensing - stars: low mass, brown dwarf

Microlensing experiments were proposed to solve one of the outstanding problems of astrophysics: the dark matter problem. They aim to detect the massive compact halo objects (MACHOs) that have been suggested as the dominant mass component of our Galaxy (Paczyński 1986; Griest et. al. 1991) through their microlensing of distant stars and the composition of the disk through observations of the bulge (Paczyński 1991). Like many astronomical observations, these experiments appear to raise new questions rather than solve outstanding problems. For while experiments that look for the halo dark matter by observing stars in the LMC appear to report too low an event rate for MACHOs to be the halo dark matter (Gould 1994), experiments that monitor stars in the Galactic Bulge appear to detect too high an event rate (Udalski et al. 1994).

Both the OGLE and the MACHO microlensing experiments find an unexpectedly large number of microlensing events towards the Galactic Bulge: 34 at the time of submission. Udalski et al. (1994) have analyzed the OGLE data and derived a very large lensing optical depth $\tau = (3.3 \pm 1.2) \times 10^{-6}$ towards the OGLE fields: Baade's window ($l = 1^o, b = -4^o$) and two adjacent fields ($\pm 5^o$, -4^o). KP and Guidice et al. (1994) find that lensing of bulge stars by stars in the disk can account for at most 20% of this observed optical depth. When KP include an axisymmetric bulge in their lensing calculations, they find that it is the dominant source of lens events. However, even their bulge plus disk model can account for only $\sim 30\%$ of the observed events and it predicts too short an event duration. KP suggest that this discrepancy may be due to their modeling the bulge as an axisymmetric rotator (Kent 1992), rather than as a bar. However, they did not make quantitative calculations of the prediction of bar models.

There is a growing consensus in the astronomical community that the Milky Way is a barred Galaxy. Binney et al. (1991) argue that a bar could explain the non-circular motions seen in both the CO and HI observations. Star counts (Nakada et al. 1992, Whitelock and

Catchpole 1992, Stanek et al. 1994) find that the characteristic magnitudes of bulge stars at positive longitudes are larger than bulge stars at negative longitudes, consistent with the bar hypothesis. Blitz and Spergel (1991) suggest that the asymmetries between the first and fourth quadrants in the IR surface brightness distribution from the balloon observation of Matsumoto et al. (1982) implies that the Galaxy is barred. These asymmetries are confirmed by recent DIRBE multicolor maps of the Galaxy (Weiland et al. 1994). Dwek et al. (1994) use these DIRBE maps to construct a three-dimensional triaxial model of the bulge, which we use to compute the optical depth for lensing towards Baade's window.

As part of the doctoral thesis, Zhao (1994) has developed a self-consistent model for the Galactic bar following Schwarzschild's (1979) method. The density profile in this model follows the Dwek et al. (1994) fit to the *COBE* image of the galaxy. This model is constructed by running 6000 stellar orbits for $\sim$ 3.5 Gigayears and then weighting these stellar orbits to match observations. In this *Letter* , we use this state-of-the-art bulge model to compute the predicted optical depth and event duration for microlensing towards the bulge.

According to KP, the optical depth averaged over all detectable stars is computed from

$$\tau = \frac{1}{\int_0^\infty ds\, w(s)} \int_0^\infty ds\, w(s) \int_0^s dl \rho(l) D\,, \tag{1}$$

where $w(s)$ is the probability of the source being at a distance s, $\rho(l)$ is the lens mass density at a distance l, and $D \equiv (s-l)ls^{-1}$ is the characteristic distance between the lens and source. The averaging over the source distance distribution is necessary, because there are events that both the lens and the source are in the bulge due to the finite depth of the bulge. Following KP, we adopt a power law luminosity function with the fraction of stars more luminous than L being proportional to $L^{-\beta}$. For a magnitude limited survey, this implies that $w(s) = \rho(s)s^{2-2\beta}$; this is probably valid within the source distance range 4 to 12 kpc. We derive a raw luminosity function from the Color-Magnitude data of Paczyński

et al. (1994), and find a good fit when β is between 0.75 and 1. Also in the range of luminosities near the magnitude limit of the OGLE, our fit to the Terndrup et al. (1990) star counts implies $\beta \approx 1.5$. Let us set $\beta = 1 \pm 0.5$; a smaller β would make a slightly larger optical depth.

Dwek et al. (1994) has fit a series of luminosity density models to the DIRBE surface brightness observations at $|b| > 3^o$. Their best fit model are the triaxial Gaussian-type models (the G1 and G2 models). The G2 model is boxy and has a density

$$\rho(x,y,z) = \frac{M}{8\pi abc} \exp\left(-\frac{s^2}{2}\right) , \tag{2}$$

where

$$s^4 = \left[\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2\right]^2 + \left(\frac{z}{c}\right)^4 .$$

The scale lengthes $a = 1.49 \pm 0.05$, $b = 0.58 \pm 0.01$ and $c = 0.40 \pm 0.01$ kpc for galactocentric distance R_0=8 kpc. The long axis of the bar, the x axis, points towards $l = -13.4^o$.

The total luminosity in Dwek et al.'s G2 model, as well as observations of stellar and gas kinematics (Kent 1992) imply a bulge mass of $\sim 1 - 2 \times 10^{10} M_\odot$. Using this, we estimate the optical depth of the bar at Baade's window to be

$$\tau_{bar} = (0.84 \pm 0.1) \times 10^{-6} M_{10} , \tag{3}$$

where M_{10} is the bulge mass in units of $10^{10} M_\odot$. When using their ellipsoidal Gaussian model (G1 model) instead, we find a 5% reduction in optical depth. τ_{bar} is also 25% smaller for the two adjacent fields ($l = \pm 5^o$, b=-4^o).

The halo is not expected to make a significant contribution to the optical depth towards Baade's window. Griest (1991) estimates the halo's optical depth towards the Bulge $\tau_{halo} \leq 0.14 \times 10^{-6}$ for a reasonable halo core radius $a \geq 4$ kpc. Also, the events due to halo objects are likely to be too short to be detectable by OGLE (Udalski et al. 1994).

The disk, however, is expected to make a significant contribution to the optical depth towards Baade's window. KP note that in the Bahcall-Soneira (BS) model the disk density along the line-of-sight towards $b = -4^o$ is nearly constant. On the other hand, infrared observations of the Galaxy (Kent, Dame, & Fazio 1991) suggest a smaller disk scale length than 3.5 kpc in the BS model; this would imply that the stellar density increases along Baade's window line-of-sight. We compute the optical depth for a double exponential disk normalized locally by the disk stellar density $\sim 0.1 \mathrm{M}_\odot \mathrm{pc}^{-3}$ (Bahcall, Flynn and Gould 1992) and the surface density of $71 \pm 6 \mathrm{M}_\odot \mathrm{pc}^{-2}$ (Kuijken and Gilmore 1991). We allow the disk to be truncated at some distance (Paczyński et al. 1994). For disk models with the full range of reasonable scale length from 2.7 kpc to 3.5 kpc (Kent, Dame, & Fazio 1991, Bahcall and Soneira 1980), the optical depth τ_{disk} is from 0.87×10^{-6} to 0.63×10^{-6} for the full disk model, and from 0.47×10^{-6} to 0.37×10^{-6} for a disk truncated at 4 kpc.

If we sum the contributions of a $2 \times 10^{10} \mathrm{M}_\odot$ bar and a truncated disk with 2.7 kpc scale length ($\tau_{disk} = 0.47 \times 10^{-6}$), then the predicted optical depth $(2.2 \pm 0.3) \times 10^{-6}$ lies within the error range of the optical depth determined by Udalski et al. (1994) from the OGLE data: $(3.3 \pm 1.2) \times 10^{-6}$. The error bar in the observed optical depth will be significantly reduced when the detection efficiency of MACHO experiment is quantified.

Unlike the optical depth, the event time scale depends on both the lens mass function and the velocity distribution of lens and source. KP note that in their axisymmetric bulge model, most of the events are expected to be of such short duration that they would not be detected in the OGLE experiment. Here, we compute the predicted event distribution in our bar plus truncated disk model and determine whether the predicted events are consistent with the OGLE observations.

Following KP, we adopt a logarithmic mass function between a mass range of $10^{-\gamma} M_\odot \leq m \leq M_\odot$ and treat γ as a free parameter. The differential lensing duration

distribution is then determined by the density distribution and the phase space distribution,

$$P(t_0) \equiv \frac{d\Gamma(t_0)}{d\log(t_0)} = \frac{16G\epsilon(t_0)}{\gamma c^2 t_0} < \int_0^s g(v,D)\rho(l)Ddl > \tag{4}$$

Here the average is over the source distance. G and c are the gravitational constant and the speed of light. $\epsilon(t_0)$ is the observation detection efficiency of events of time scale $t_0 \equiv R_E/v$; for OGLE, we find $\epsilon(t_0) = 0.3\exp(-(t_0/11\text{day})^{-0.7})$ is a convenient and good interpolation of values given in Udalski et al. (1994). The dimensionless factor g is the phase space fraction of sources and lenses whose relative proper motion velocity satisfies

$$2r_{\rm low}D \le v^2t_0^2 \le 2r_{\rm upp}D\,, \tag{5}$$

where $r_{\rm low} = 2GM_{\rm low}c^{-2}$ and $r_{\rm upp} = 2GM_{\rm upp}c^{-2}$ are the Schwarzchild radius corresponding to the lower and upper mass cutoffs. In our calculations, we evaluate g by Monte-Carlo integration over the six-dimensional phase space.

Before turning to our self-consistent bar model to compute g, we can estimate the event time distribution by approximating the relative proper motion distribution as a 2-D Gaussian of transverse velocity dispersion σ_t:

$$g \approx \exp\left(-\frac{r_{\rm low}D}{\sigma^2t_0^2}\right) - \exp\left(-\frac{r_{\rm upp}D}{\sigma^2t_0^2}\right) \approx \exp\left(-\frac{r_{\rm low}D}{\sigma^2t_0^2}\right)\,. \tag{6}$$

The steep drop-off of g and $\epsilon(t_0)$ for short events, together with the t_0^{-1} drop-off for long events, implies that $P(t_0)$ peaks near

$$t_p = (t_\epsilon^2 + R_E^2\sigma_t^{-2})^{0.5}\,, \tag{7}$$

where the time scale t_ϵ= 7 days is due to the steep drop-off of OGLE detection efficiency for very short events, and the characteristic Einstein radius R_E = (80 day $\times$ 100 km s^{-1})$M_{\rm low}^{0.5}D_{\rm kpc}^{0.5}$. A more massive lens and a larger distance between the lens and the source makes a larger Einstein radius. Together with a lower transverse dispersion, it shifts the

distribution towards longer duration. The Spaenhauer et al. (1992) analysis of proper motion data in Baade's window finds $\sigma_t \equiv (\sigma_l^2 + \sigma_b^2)^{1/2} = 150$ km s^{-1}. We estimate that the average characteristic distance $D \simeq 0.75$ kpc in the Dwek G2 model. So a model with most lenses being brown dwarfs and the lower mass cutoff at $10^{-2} M_\odot$ would predict a peak in duration distribution at about 8 days, while OGLE detected events with duration ranging from 8 to 62 days.

We can improve our estimate of event distribution by using Zhao's (1994) self-consistent bar which fits the G2 model of Dwek et al. (1994), the radial velocity and proper motion dispersions at Baade's window (Sharples et al. 1990, Spaenhauer et al. 1992, Zhao et al. 1994) and a mean stellar rotation curve of slope 60 km s^{-1}kpc^{-1} (e.g., Izumiura et al. 1992). Our galactic potential consists of the G2 model for the bar, a Miyamoto-Nagai potential for the disk and an isothermal dark halo (Binney & Tremaine 1987). The bar mass is fixed at $2 \times 10^{10} M_\odot$ with a pattern speed of 60 km s^{-1}kpc^{-1} similar to the Binney et al. (1991) model. The disk parameters are fit to the BS model and the halo parameters are fixed so that the rotation curve is flat out to 20 kpc. The stellar distribution function is composed of the weighted sum of 6000 orbits, each of which has been run for 1024 orbit crossings. Quadratic programming (e.g., Merritt 1993) is used to assign weights to each of these orbits so that their sum reproduces the G2 model and the observed kinematics.

In Figure 1, we plot the transverse velocity dispersion σ_t (solid line) and the absolute value of transverse rotation speed V_t (dashed line) in km s^{-1} from Zhao (1994) bar model, and the arbitrarily scaled probability of lens location (dotted line) as functions of distance from the Sun along Baade's window line-of-sight. The probability includes the disk lenses. As both the disk and the bulge are truncated at 4 kpc, there is a break in lens density at the truncation point. Note that most of the lenses are at 6.25 kpc in the Bulge, well in front of the sources. The large Einstein radius, together with the low transverse velocity

dispersion at the most probable location of lenses, shifts the event distribution towards longer duration in the Galactic bar model.

Using this bar model, we can directly evaluate g by a Monte-Carlo integration over the stellar distribution function. Combining this result with the reported OGLE efficiencies yields our prediction for the event duration distribution in the OGLE experiment. A truncated small scale length disk is also included in the calculation with a disk velocity distribution same as KP. Figure 2 shows event duration distributions of the OGLE data (histogram) from Udalski et al. (1994) and models with the lower mass cutoffs at $10^{-1}M_{\odot}$ (solid line) and $10^{-2}M_{\odot}$ (dotted line). The upper panel shows the normalized cumulative distribution. The lower panel shows the differential distribution. The model with cutoff at $10^{-2}M_{\odot}$ predicts too many short duration events; a KS test finds only a 7% probability that it is consistent with the data. The observations appear to favor higher cutoff; the model with $10^{-1}M_{\odot}$ cutoff predicts 5 to 7 microlensing events detectable by OGLE with a typical time scale of 20 days. These results hint that there are few brown dwarfs in the Bulge. A larger sample will enable more definitive determination of the bulge mass function.

In summary, stars in the galactic bar are the major source of optical depth for microlensing in the Baade's window fields monitored by the OGLE program. Using a self-consistent bar model that has been fit to the DIRBE observations of the bulge surface brightness distribution and to the observed stellar kinematics, we have computed the optical depth towards Baade's window and the predicted event duration distribution. We find that the bar model provides a better fit to the microlensing observations than an axisymmetric model for the Galaxy. The optical depth of the bar model is consistent with the OGLE value. The OGLE observed event duration distribution also favors models with few brown dwarfs in the Bulge.

Future observations of stars in the bulge will test the hypothesis that ordinary stars

in the bar are the dominant microlenses. When the MACHO efficiency is quantified, the event duration distribution in this experiment can also be compared to our theoretical predictions. Since the lens probability is strongly peaked near 6.25 kpc in our model, most of the lenses should be observable by Hubble Space Telescope: for A_I=1 magnitude in Baade's window, 0.1 $M_\odot$ stars ($M_I \simeq 12$) should have I$\simeq$ 27. Eventually, the detection of microlensing events at several fields can determine the distribution of lenses and provide a definitive determination of the nature of the dominant microlenses.

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Fig. 1.— shows the predicted transverse velocity dispersion σ_t (solid line) and the absolute value of transverse rotation speed V_t (dashed line) in km s^{-1}, and the arbitrarily scaled probability of lens location (dotted line) as functions of line-of-sight distance along Baade's window. Note that the bar model predicts that most of the lenses are at 6.25 kpc in the Bulge, where σ_t is also low. The break in lens density near 4 kpc is due to truncation.

Fig. 2.— shows event duration distributions of the OGLE data (histogram) and models with the lower mass cutoffs at $10^{-1}M_\odot$ (solid line) and $10^{-2}M_\odot$ (dotted line). The upper panel shows the fraction of events $f(< t_0)$ with duration shorter than t_0. The lower panel shows the logarithm of $P(t_0)$, the predicted rate of microlensing events per 10^6 bulge stars per year, as function of time scale t_0. The observations appear to favor the model with higher cutoff.